DESIGN OF AN EXHAUST GAS CALORIMETER FOR AUTOMOBILE ENGINES

BY

J. L. MAYER

L. E. HIBBARD

ARMOUR INSTITUTE OF TECHNOLOGY

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DESIGN OF AN EXHAUST GAS CALORIMETER FOR AUTOMOBILE ENGINES

A THESIS

PRESENTED BY

J. LEO MAYER
LEWIS E. HIBBARD

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G. F. Gebhardt 5/25/15

H. M. Raymond

L. C. Monin

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INTRODUCTION.

At present very little data is available as to the amount of heat wasted or lost in the sensible heat of the exhaust gases of gas engines. This amounts to about 30 or 40 percent of the total available heat, and should be determined more accurately than by rational calculations and temperature entropy diagrams.

At present the method is to obtain the temperature of the exhaust, assuming a specific heat, calculate the weight from the volumetric efficiency, and then calculate the heat lost.

Recognizing the need of more accurate information on this phase of gas engine analysis, it was decided to design and construct an EXHAUST GAS CALORIMETER for High Speed Automobile engines.

PERSONNEL.

The tests were made under the general direction of G. F. Gebhardt, Professor in charge of the Mechanical Engineering Department, and the personal supervision of Asst. Professor D. Roesch.

Valuable assistance was rendered by Messrs. Bready, Ward and Chipman.

OBJECT.

The object of this thesis is to design, construct and test an EXHAUST GAS CALORIMETER for High Speed Automobile engines, and to determine whether any rational equations governing the sensible heat of the exhaust gases hold true, and if not, what the variations are.

SCOPE OF REPORT.

This thesis is divided into three parts. In the first part is given a complete description of the calorimeter, including its design and method of construction. The second part is devoted exclusively to the description of the engine and its accessory apparatus. The third part, in addition to the results and method of testing, contains a discussion of the results obtained. The fourth part contains our conclusions.

It is believed that the results achieved with the equipment described warrant a more extended research into this phase of gas engine analysis.

PART ONE.

DESCRIPTION OF CALORIMETER,
ITS DESIGN
AND METHOD OF CONSTRUCTION.

THEORY OF CALORIMETER.

The heat to be measured is to be imparted to a stream of water. The weight of water flowing through the calorimeter during the time that a known volume of combustible is consumed in the engine and the resultant temperature of the water, furnish the data necessary to calculate the heat imparted to the water. There is, however, a loss of heat through the calorimeter, the magnitude of which will be neglected in this treatise.

The temperature of the water entering and leaving the calorimeter is measured by means of inlet and outlet thermometers. A large body of water must be provided in the bottom of the calorimeter to thoroughly mix the water before it reaches the outlet thermometer cup, in order that

the thermometer shall indicate the true mean temperature of the effluent water.

The rate of flow of water, and hence its rise in temperature is varied by means of suitable valves in the supply line.

DESIGN OF CALORIMETER.

The calorimeter was designed for a six cylinder engine, 450 cu. inches piston displacement and 2000 R.P.M.

$$\frac{450 \times 2000}{2 \times 1728} = 260 \text{ cu. ft. gas per minute}$$

Specific heat of gas = approx. 24

Density = approx. .1(avCO_2,N_2)

260 x .24 x.1 = 6.24 BTU per degree difference in temperature.

Assume temperature of exhaust = 900 deg. F.

Assume room temperature = 70 deg. F.

6.24 x (900-70) = 51,800 B.T.U. per min.

Assume 30 degree raise in temperature of water. $\frac{51,800}{30} = 173$ lbs. water per min.

Assuming a velocity of 650. ft. per min. for the exhaust gases area of passage must be $\frac{260}{650} = .40$ sq. ft. = 58 sq. in.

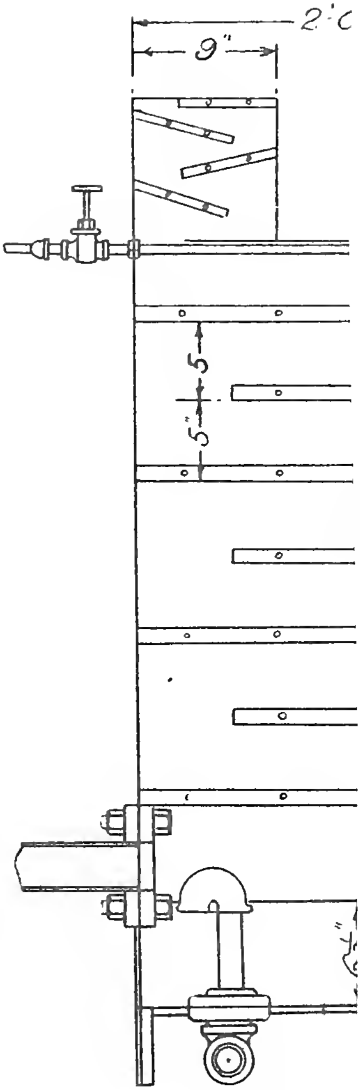
The passage ways were made 5" x 12".

GENERAL DESCRIPTION OF CALORIMETER.

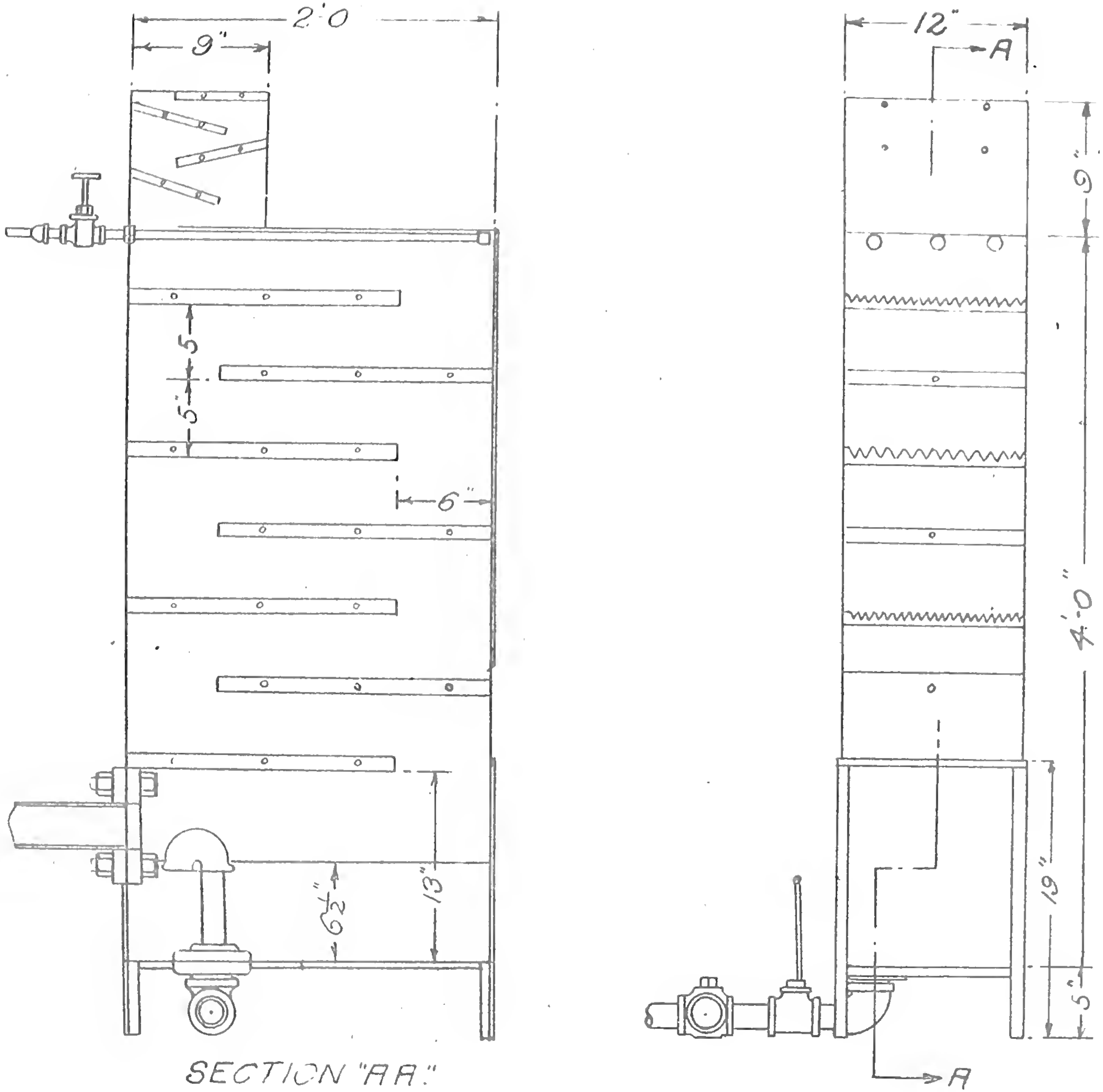
The calorimeter is of the counter current, rain type, with a series of dry baffles to separate any mechanically entrain ed water. A sectional view of the calorimeter may be seen on the accompanying sketch, Fig. 1.

There are seven wet baffles and five dry baffles. The latter are located in the tower of the calorimeter.

The water enters in the upper wet pass, and is sprayed by means of three one and one-half inch pipes perforated with one hundred and fifty one-sixteenth holes. The water falls to the top baffles, and is then precipitated over the saw tooth edge in the form of rain. The water falls from baffle to baffle until it reaches the bottom. Here it is subjected to the direct heat of



SECTION



CALORIMETER
WITH DOOR OFF

Fig. 1.

the incoming gases. A space is provided for a large body of water in the bottom, approximately seventy pounds, so that it may be thoroughly mixed and have a fairly constant temperature. It passes out of the cal orimeter through a water seal, and then through a three way cock where it may be directed to either the sewer or a weighing tank.

The amount of water flowing through the calorimeter may be regulated by means of three one-half inch valves in the supply line. The object being to reduce the gases to as near room temperature as the sensitiveness of the calorimeter will permit.

DETAILED DESCRIPTION OF CALORIMETER.

The body of the calorimeter was made of Number 26 galvanized iron, all seams double soldered.

An opening with a removable cover was put in the upper end of the calorimeter to facilitate the proper spacing of the baffles, and also that the action of the saw tooth edge of the baffles could be observed.

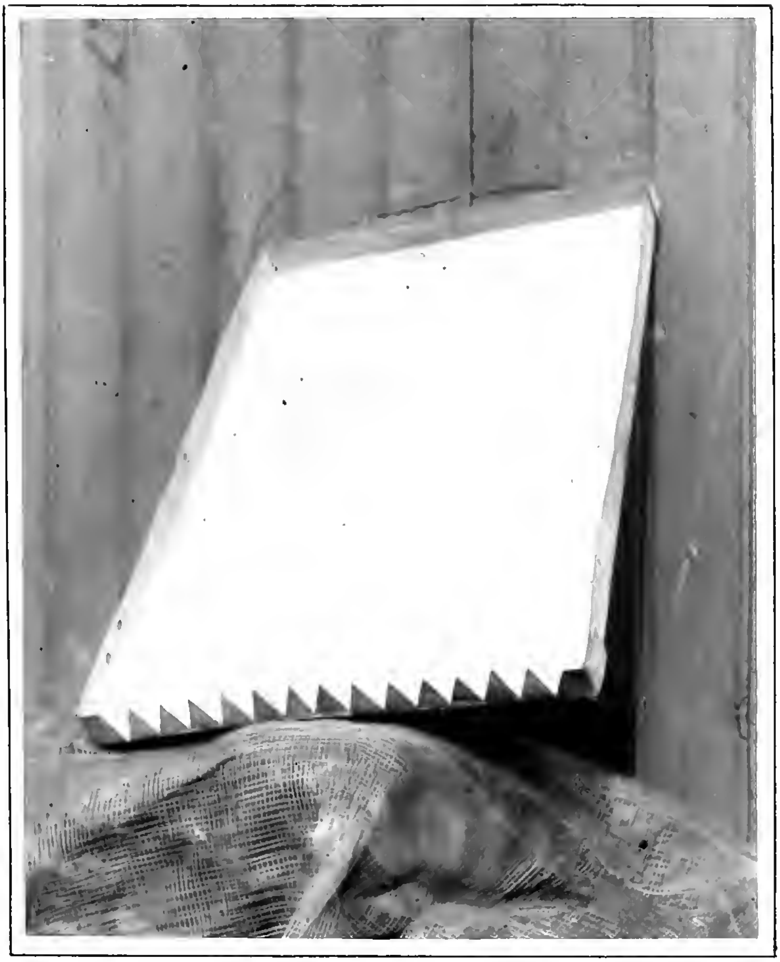
The water is led to the calorimeter by means of a one-inch pipe to a one-inch header, to which the spray pipes and regulating valves are attached. The gases are prevented from short circuiting by means of an inch and a quarter return elbow. The return elbow also serves to keep the water lev el in the calorimeter fairly constant. The elbow is screwed onto a five inch by one and

a quarter inch nipple which in turn is connected to flanges bolted to the bottom and made water tight by means of suitable gaskets.

After leaving the calorimeter the water is lead past a thermometer cup to a three way valve, where it may be lead either to a weighing tank or the sewer.

The baffles are 12" x 18" and are placed parallel to the bottom to facilitate in conjunction with the saw tooth edges the rapid cooling of the gases due to the quantity of water held on the baffle. A photo of baffle may be seen on Page 18.

The tower, that is the compartment above the spraying chamber has five wet baffles which act as a separator. These baffles are placed at a slight angle with the horizontal to allow any precipitated moisture to



fall back into the calorimeter.

The gases enter in the lower pass about an inch above the water level through a three inch pipe with suitable flanges and high temperature gaskets. The gases are directed upwards, back and forth and around the baffles, during which time they pass through seven cascades of water, and through the final spraying chamber and thence to the separator. From here they may be allowed to escape to the atmosphere or be run through a meter and measured.

The calorimeter is supported six inches above a table by means of an angle iron frame. This is to allow sufficient room for the exit cooling water pipe.

PART TWO.

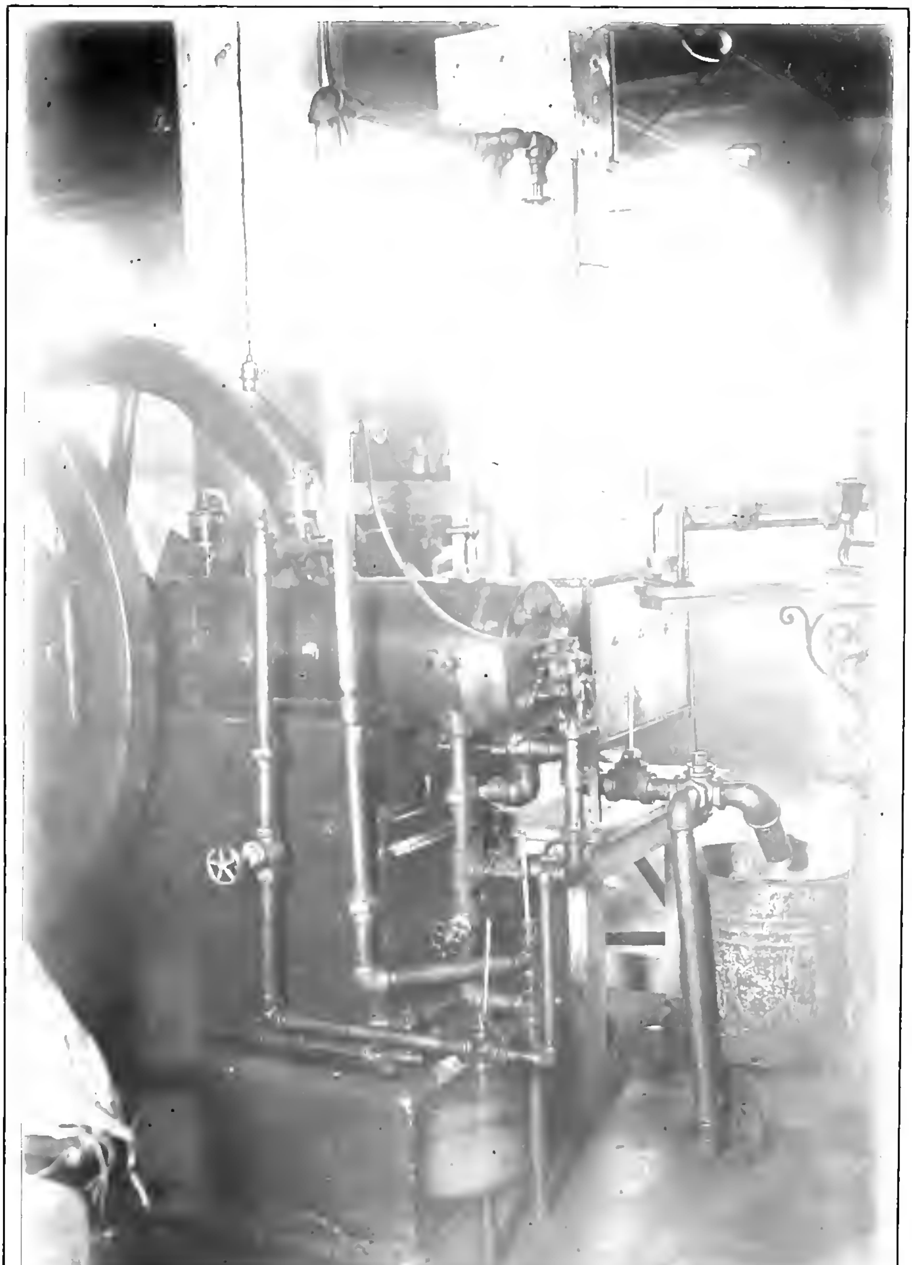
DESCRIPTION OF ENGINE

AND

ITS ACCESSORY APPARATUS.

As the automobile engines which were available would necessitate a reconstruction of their exhaust manifolds, it was decided to attach the calorimeter to the Fairbanks-Morse engine, which engine is rated at seven horsepower at 260 R.P.M., the diameter of the cylinder being 6-3/4 inches, with a stroke of 11-15/16 inches.

The valves are of the poppet type. The inlet valve in the head of the cylinder works automatically, while the exhaust valve is operated mechanically by means of a cam which is driven by gears from the main shaft. The speed of the engine is controlled by means of a centrifugal governor which acts on the "hit or miss" principle, that is, when the engine exceeds the normal speed of the governor the mechanism holds the exhaust valve open. The motion of this valve by means of a series of levers, operates a valve in the gas line, which regulates the



supply of fuel to the engine.

The ignition is effected by means of a cam on one of the gear wheels. The motion of the cam is transmitted by means of a shaft to a lever which makes and breaks the circuit in the igniter, The igniter can be set at two positions by means of an ignition lever, the late position makes the spark or point of ignition at 10 degrees late, This position is only used for starting the engine. The other position is 7 degrees early, and is used for the regular running of the engine.

ACCESSORY APPARATUS.

The load is given the engine by means of a prony brake. This brake is on a water cooled pulley which is keyed to the main shaft, and consists of a number of wooden blocks held together by iron bands. These bands are split at the top and can be adjusted by means of a bolt and nut.

A Crosby Indicator was used to obtain cards from the engine. A 20 pound spring fitted with a stop to prevent the indicator piston from rising too high, was first used to get the pressures in the cylinder during the idle stroke, that is, the suction and the exhaust strokes. This diagram is used for obtaining the back pressure caused by the friction of the gases in the exhaust passages, and in the calorimiter.

The calorimeter was connected to the engine by means of a two and one-half inch nipple bushed into a three inch flange of the calorimeter. The one-inch header was connected to the service line by means of a one-inch pipe and suitable fittings.

The other accessory apparatus consisted of weighing tanks and scales for weighing the jacket water, also a tank and box and scale for weighing the calorimeter water; revolution and explosion counters; thermometers for measuring the temperatures of the room, gas inlet and outlet jacket water, and inlet and outlet calorimeter water; prony brake; scale; indicator and manometer for obtaining the pressure of the gas at the meter, and a Junker calorimeter with its accessory apparatus for determining the heat content of the fuel gas.

PART THREE.

RESULTS AND DISCUSSION.

INTRODUCTION.

The general condition of the engine would not permit runs of sufficient duration to be made; so that the data embodied in this report is not to be relied upon for any degree of exactness.

As the conditions imposed on us during the tests, compelled us to take only the absolutely essential data, it was deemed advisable to take but one reading on the Junkers Gas calorimeter.

Throughout the runs the usual data for any engine tests were taken, and in addition the various calorimeter readings.

While it would have been advisable to make an analysis of the exhaust gas by means of an Orsat apparatus in order to determine the character and amount of unburned gases, as previously stated, conditions prohibited us from making this analysis.

PRELIMINARY RUN.

After the apparatus had been assembled a preliminary run was made. During the course of this run several minor water leaks developed. A breathing action caused by the hit or miss type of governing was observed in the lower wet pass. It was decided that this was too pronounced for safety; accordingly three lateral horizontal stays and one longitudinal stay, all made of one-quarter inch soft steel rods, were added.

The cover over the observation opening bulged considerably, due to the back pressure andlack of sufficient strength. It was decided that the quickest and most efficient way toremedy this was to put boards over the ends and hold them together by means of tie rods. After makibg these changes a complete test was made, varying the load from zero to a maximum. Consider-

able trouble was encountered in procuring the desired temperatures of the exhaust gas and water.

The calorimeter which was designed for a six cylinder engine five times as large as the Fairbanks-Morse Engine was found to be too large. When the amount of water used was cut down so that the exhaust gases woukd issue at room temperature, it would steam in the lower wet pass. When enough water was admitted so that moderate temperatures were secured in the lower pass, the issuing exhaust gas was too cool. It was also found that the calorimeter had a considerable lag, that is, any adjustment of the regulating valves brought instantaneous decrease in the temperature of the exhaust gas, but did not change the issuing water until several minutes later.

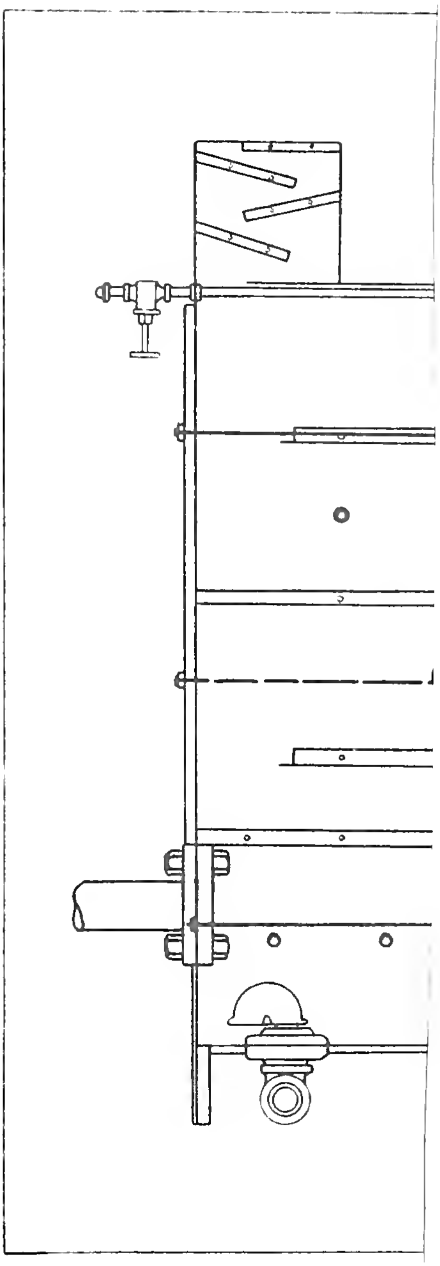
RECONSTRUCTION OF CALORIMETER.

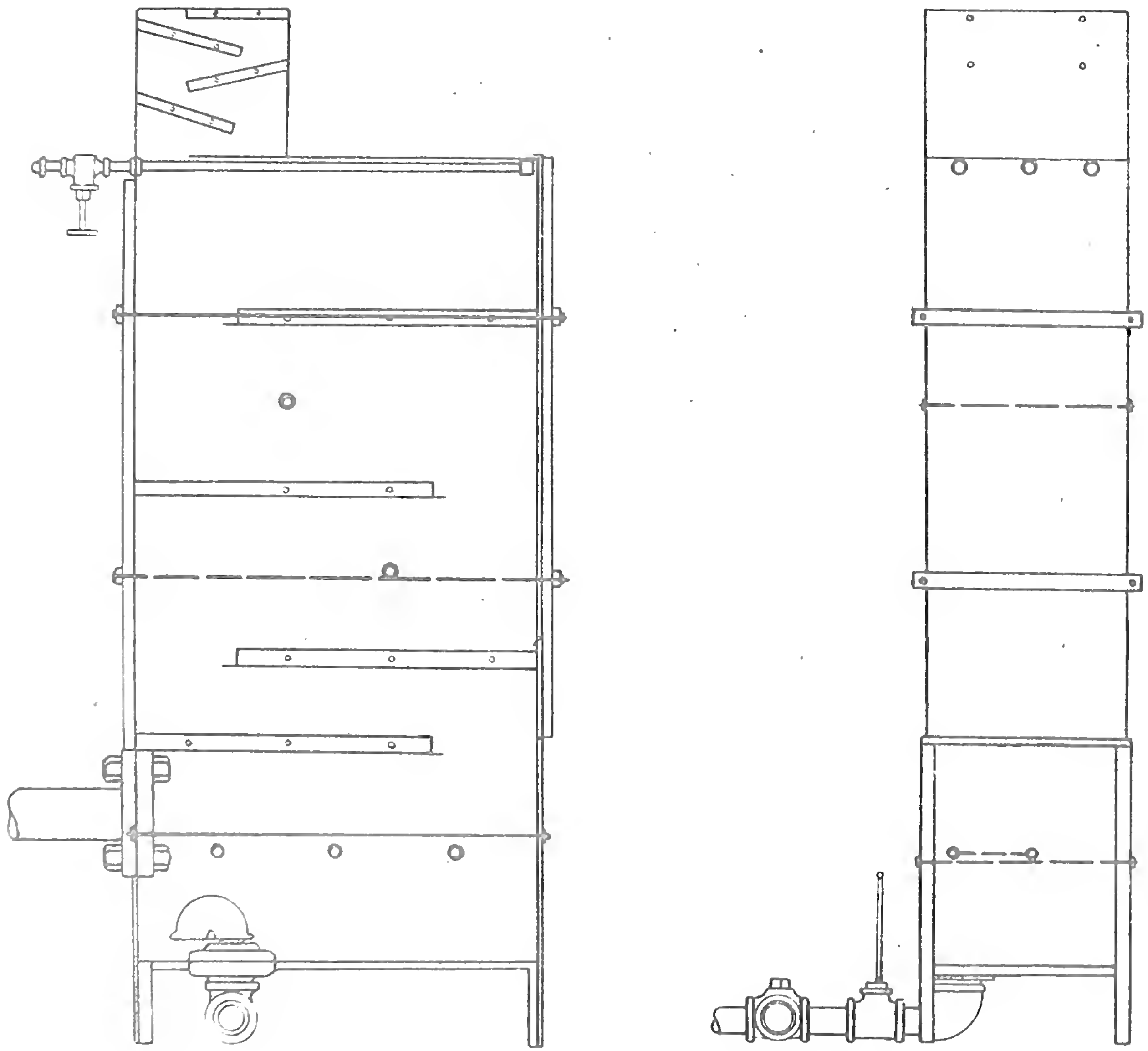
It was, therefore, decided that, in order to obtain the desired results from this engine, it would be necessary to cut down the amount of water contained in the calorimeter, and also by-pass the spraying chamber, and cut out several passes. A drawing of the reconstructed calorimeter is shown on the preceeding page.

To facilitate more instantaneous operation the quantity of water was cut down in the lower wet pass by shortening the nipple on the water seal, and by bending over the saw tooth edges so that a minimum amount of water was stored on the baffles.

A photograph of the reconstructed baffle is shown on page 32.

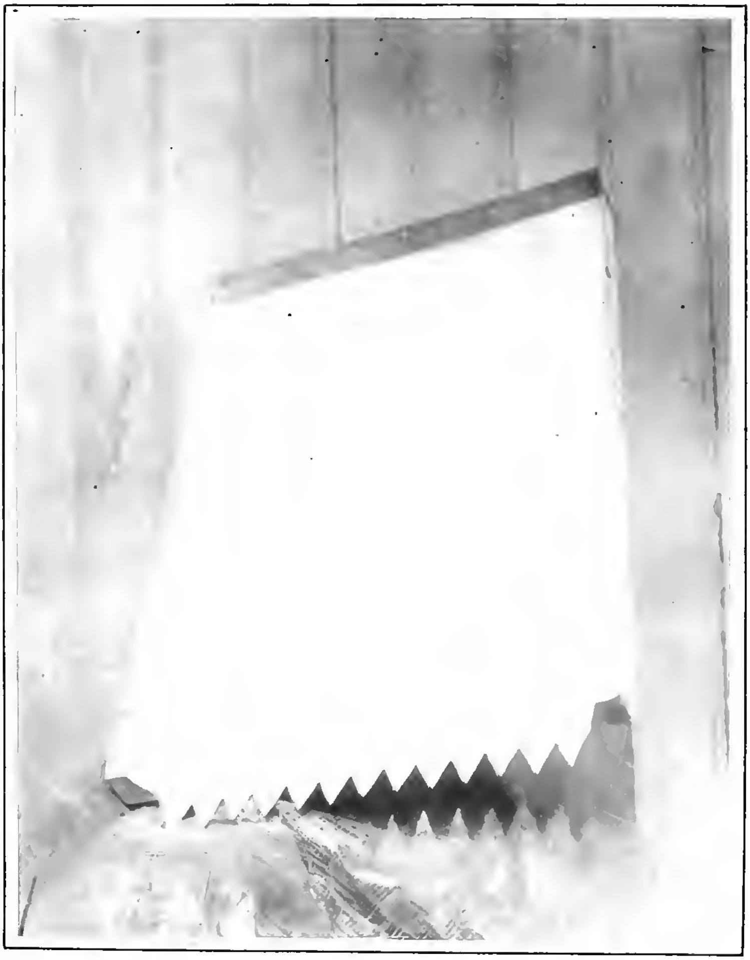
After the above-mentioned changes had been made, another complete run was made.





RECONSTRUCTED
VIEW OF
CALORIMETER

Fig 4



It was found that the previous mentioned objections, the bulging, breathing and refrigerating effect and the short circuiting of gases through the exit pipe and the lag of the calorimeter had been remedied.

During the preliminary run and the run before the calorimeter was reconstructed, the brake arm rested on two places. This made the results of the first two tests unreliable, and were, therefore, discarded.

Another notch was filed in the brake arm, and the brake constant recalculated.

TEST OF

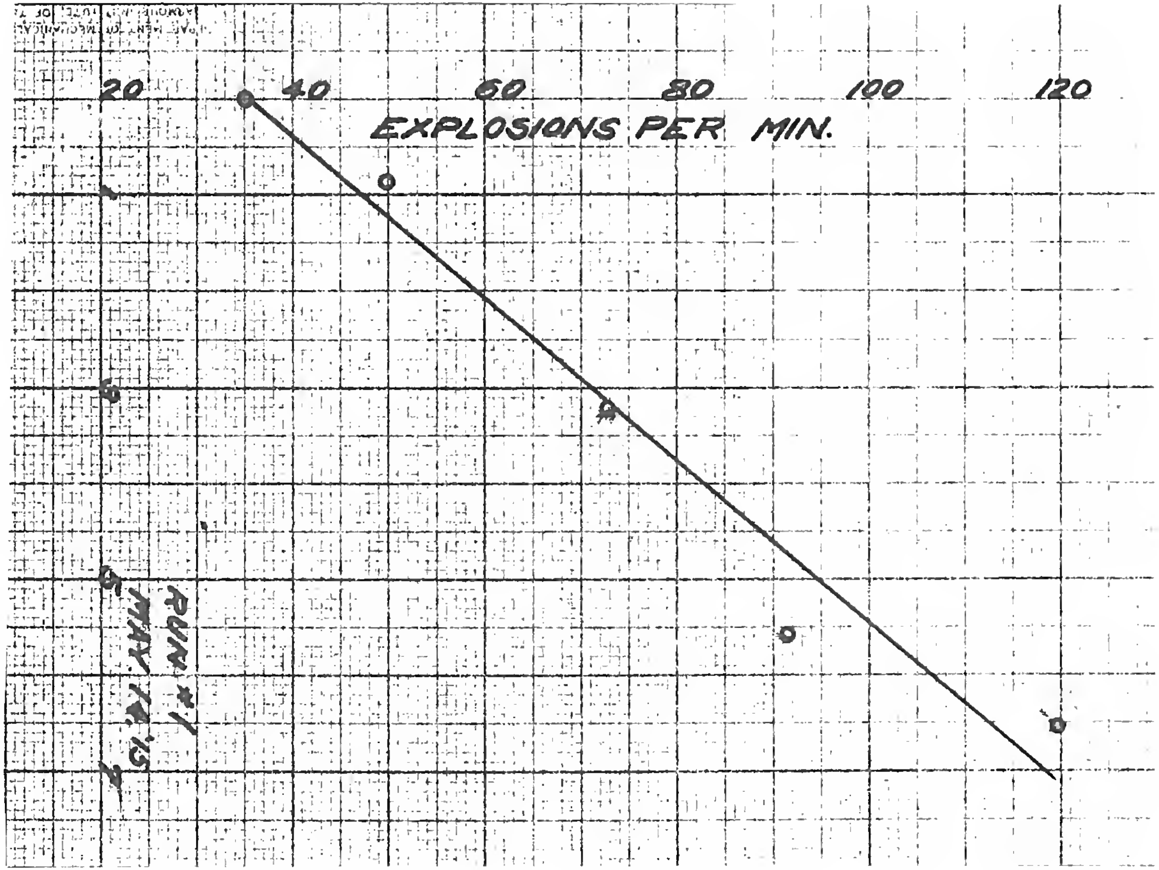
DURATION OF RUN
NET LOAD ON BRA
GAS CONSUMED
CALORIFIC VALUE
JACKET WATER F
GAS PER HR
GAS AT METER
BAROMETER
CALORIMETER WAT
SUPPLY WATE
JACKET WATE
GAS AT METER
ROOM
EXHAUST
CALORIMETER WAT
R. P. M.
EXPLOSIONS PER
M.E.P
I.H.P
B.HP
MECH EFF.
HEAT SUPPLIED P
HEAT IN JACKET
HEAT IN EXHAUST
HEAT EQUIVALENT
HEAT IN JACKET
HEAT IN EXHAUST
HEAT PER I.HP
HEAT IN EXHAUST (C

TEST OF FAIRBANKS MORSE GAS ENGINE

RUN #1

MAY 14, 1915.
J.L. MAYER L.E. HUBBARD

DURATION OF RUN	MIN	10	15	8	12	5
NET LOAD ON BRAKE	LBS.	0	7.7	27.7	47.7	67.7
GAS CONSUMED	CU.FT. STD.	9.27	20.95	19.3	28.55	16.7
CALORIFIC VALUE OF GAS	TOTAL	705	705	705	705	705
JACKET WATER PER HR	LBS	4152	900	1012.5	765	900.
GAS PER HR	CU. FT. STD.	55.67	83.8	144.75	142.75	200.4
GAS AT METER	IN. HG.	29.57	29.57	29.57	29.57	29.57
BAROMETER	IN. HG	29.43	29.43	29.43	29.43	29.43
CALORIMETER WATER OUTLET	°F	84	84.75	100.5	106.5	90.3
SUPPLY WATER INLET	°F	53	53	53	53	53.
JACKET WATER OUTLET	°F.	56	74.2	86.5	106.	98.3
GAS AT METER	°F.	62	62	62	62	62.
ROOM	°F.	60	59	58	58.	59.5
EXHAUST	°F.	60	61	64	62.5	60.0
CALORIMETER WATER PER HR.	LBS	345.0	604.	641.25	600.0	1270.
R. P. M.		268.5	265	267.	267.	244.
EXPLOSIONS PER MIN.		35.5	50	73.5	90.5	120
M.E.P.	LBS	83.9	75.9	72.5	73.5	70.1
I.H.P.		3.85	4.91	5.95	7.20	9.18
B.H.P.		0	.876	3.12	5.43	7.03
MECH EFF.	%	0	17.8	52.3	75.3	76.5
HEAT SUPPLIED PER HR.	B.T.U.	39200	59100	102,000	100,700	141000
HEAT IN JACKET	B.T.U.	12,450	19,100	35100	40,500	40800
HEAT IN EXHAUST	B.T.U.	10,700	18,750	30,500	32,100	47,000
HEAT EQUIVALENT OF I.H.P.	B.T.U.	9,550	12,500	15150	18,350	23,400
HEAT IN JACKET	%	31.8	32.15	34.4	40.1	29.0
HEAT IN EXHAUST	%	28.3	31.7	29.8	31.8	33.3
HEAT PER I.H.P.	%	24.4	21.1	14.8	18.2	16.6
HEAT IN EXHAUST (CALCULATED)	%	19.7	18.3	17.15	19.7	18.55


20
40
60
80
100
120
EXPLOSIONS PER MIN.
1
3
5
7
RUN #1
MAY 14 '15

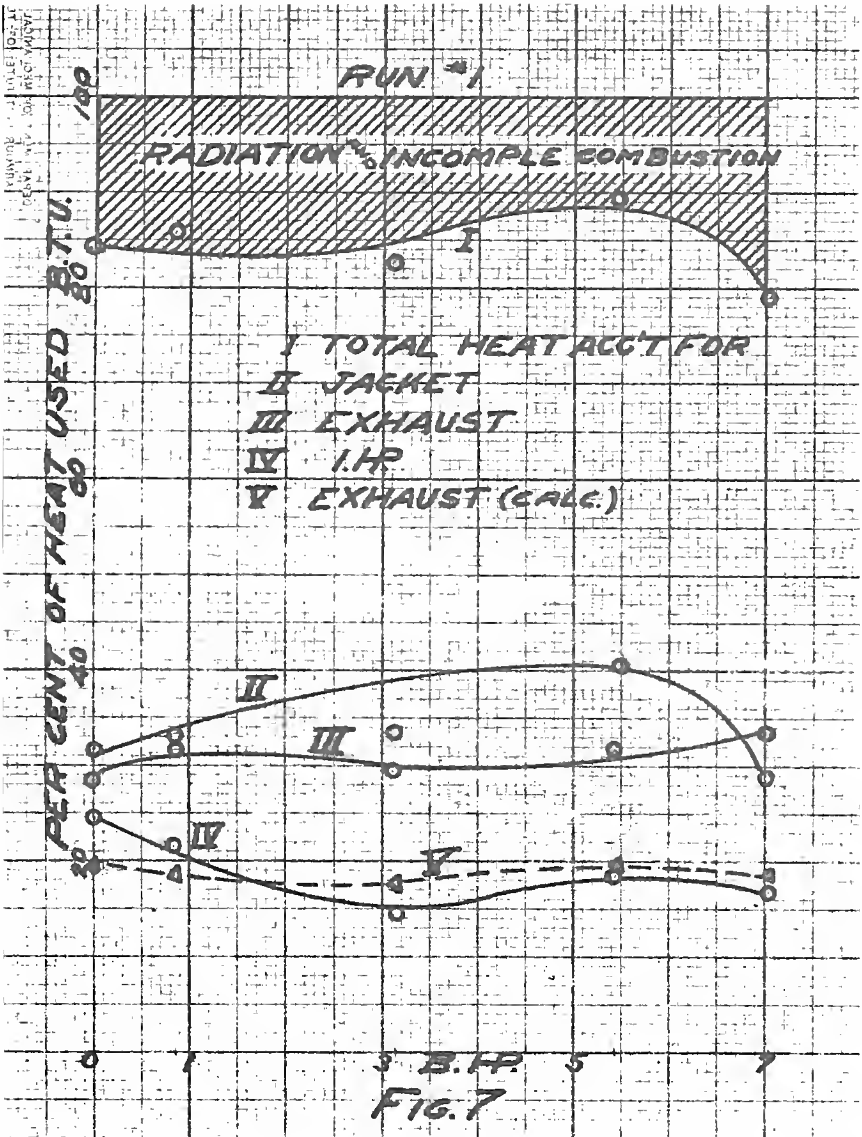

RUN #1
RADIATION & INCOMPLE COMBUSTION
I TOTAL HEAT ACC'T FOR
II JACKET
III EXHAUST
IV I.H.P.
V EXHAUST (CALC.)
PER CENT OF HEAT USED B.T.U.
100
80
60
40
20
0
1
3
B.H.P.
5
7
I
II
III
IV
V

FIG. 7

RUN NUMBER 1.

During this run the mixing valve was inadvertently changed so that this data, when plotted, as shown in Figure 7, Page 37, did not give uniform results.

There was considerable leakage of exhaust gas and water in the top of the spray ing chamber, due to back pressure. As the gas had already given up its heat to the water, and as the water at this point had received very little heat from the gas, it was decided to neglect this entirely.

TE

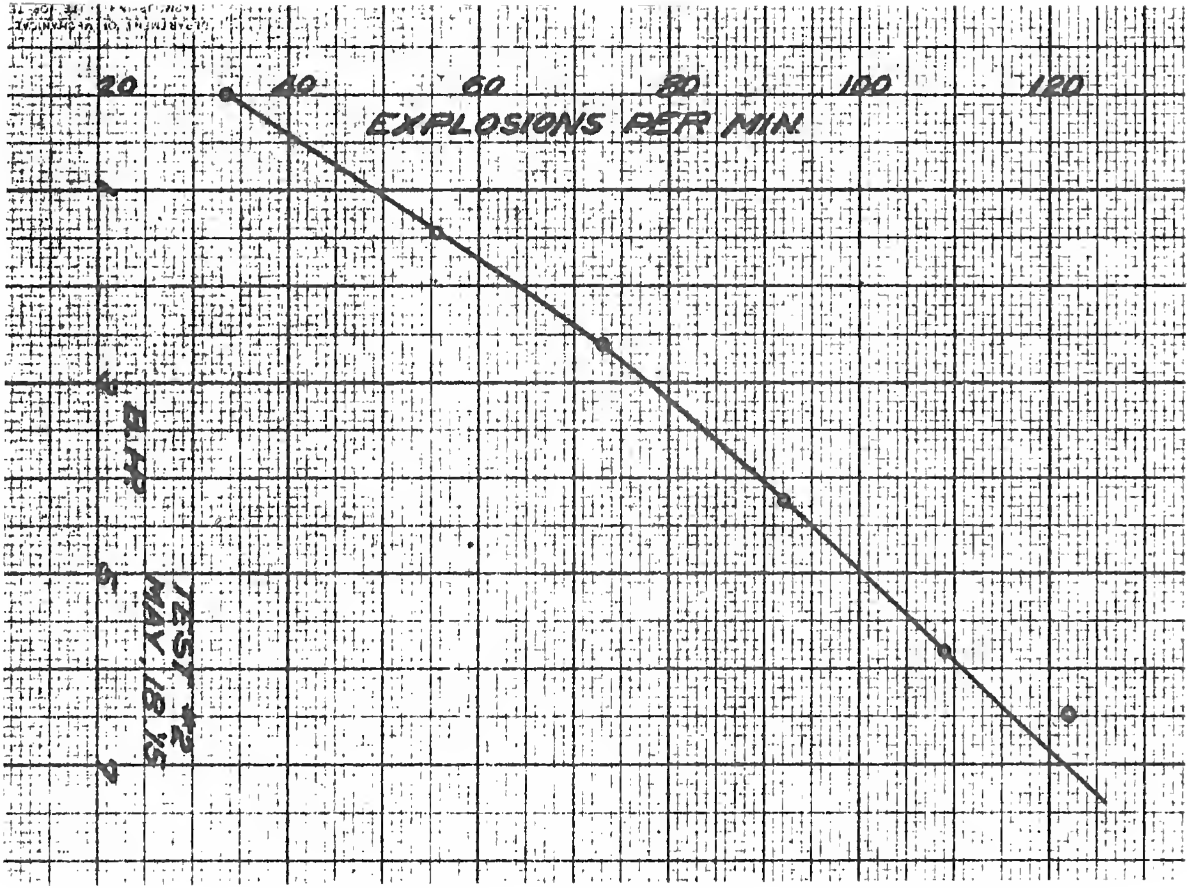
DURATION OF
NET LOAD ON
GAS CONSUME
CALORIFIC VA
JACKET WATE
GAS PER HR.
GAS AT MET
BAROMETER
CALORIMER WAT
SUPPLY INLET
JACKET OUTLE
GAS AT METE
ROOM TEMP.
EXHAUST
CALOR. WATE
R.P.M.
EXP. P.M.
M.E.P.
ACTUAL I.H.P.
ACTUAL B.H.P.
MECH. EFF
B.T.U. SUPPLI
HEAT IN JAC
HEAT IN EXH
" EQUIVA
" "
" IN EXH
" " JACK
" " EXHA

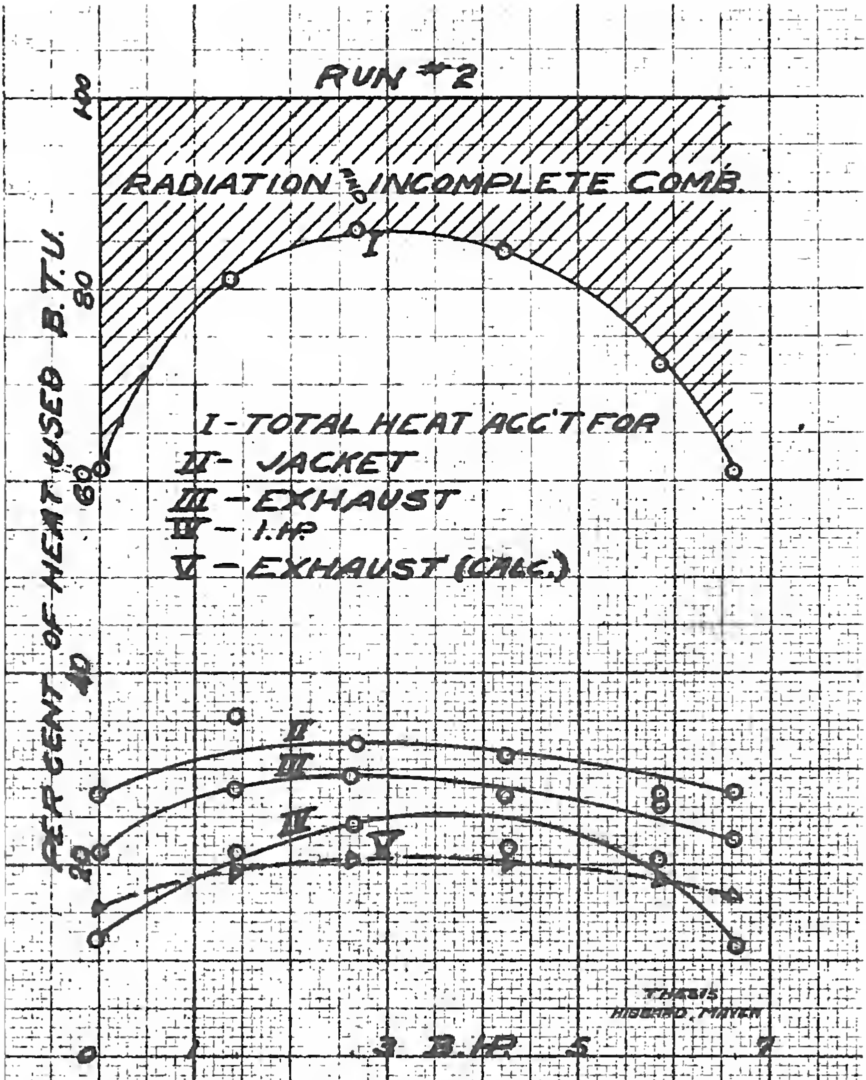
TEST OF FAIRBANKS MORSE GAS ENGINE

RUN #2.

MAY 18 1915 —
J.L. MAYER L.E. HIBBARD

DURATION OF RUN	MIN.	10	10	10	10	10	5
NET LOAD ON BRAKE	LBS.	0	12.7	22.7	37.7	52.7	62.7
GAS CONSUMED	CU. FT. (STD.)	10.6	13.7	17.5	22.0	28.6	18.7
CALORIFIC VALUE OF GAS	B.t.u	705	705	705	705	705	705
JACKET WATER PER HR	LBS.	807	705	540	564	704	895
GAS PER HR.	CU. FT. (STD.)	64	82.5	105	132	170	224.3
GAS AT METER	IN. HG.	29.98	29.98	29.98	29.98	29.98	29.98
BAROMETER	IN. HG.	29.65	29.65	29.65	29.65	29.65	29.65
CALORIMER WATER OUTLET	°F.	76	75	80	99	88.5	82.5
SUPPLY INLET	°F.	53	53	53	53	53	53
JACKET OUTLET	°F	69	81.5	97	104.7	99.7	102
GAS AT METER	°F	58	59	62	65	68	60
ROOM TEMP.	°F	56	56	58.5	58	60	57.5
EXHAUST	°F	57	56.6	58.5	62	61	60
CALOR. WATER PER HR.	LBS.	395.4	492.0	817.5	549.0	933.0	1194.0
R.P.M.		265.5	267.0	270.0	264.5	260.0	244.0
EXP. P.M.		33.5	55.5	73.0	91.6	105.5	122.
M.E.P.	LBS.	71.3	68.	67.5	6.66	70.4	65.2
ACTUAL I.H.P.		3.1	4.88	7.12	7.9	9.6	10.6
ACTUAL B.H.P.		0	1.45	2.61	4.25	5.85	6.65
MECH. EFF.	%	0	28.6	36.6	53.8	60.8	62.7
B.T.U. SUPPLIED PER HR	B.T.U.	45200	58200	74000	93000	120,000	158000
HEAT IN JACKET	B.T.U.	12,900	20,500	23,800	29,200	32,900	43,800
HEAT IN EXHAUST	B.T.U.	9,700	11300	22,100	25300	32,100	35,160
" EQUIVALENT I.H.P.	B.T.U.	7,890	12,410.	18,120	19850	24,420	25,900
" " "	%	17.4	21.3	24.5	21.3	20.3	16.4
" IN EXHAUST	%	21.2	19.4	29.9	27	26.7	22.2
" " JACKET	%	27.5	35.2	32.6	31.4	27.4	27.7
" " EXHAUST (CALCULATED)	%	15.5	19.9	20.6	20.65	18.5	16.3


20
40
60
80
100
120
EXPLOSIONS PER MIN.
1
3
5
7
B.H.P.
TEST #2
MAY. 18. '15



RUN #2
RADIATION & INCOMPLETE COMB.
I - TOTAL HEAT ACC'T FOR
II - JACKET
III - EXHAUST
IV - I.H.P.
V - EXHAUST (CALC.)
PER CENT OF HEAT USED B.T.U.
100
80
60
40
20
0
1
3
B.H.P.
5
7
I
II
III
IV
V
THESIS
HIBBARD, MAYER

FIG. 9.

RUN NUMBER 2,

During this run the mixing valve was set in one position, and care was taken that its adjustment was not changed.

When the engine was run at its rated power considerable trouble was experienced in making the engine hold its load. Its operation was accompanied by occasional back-firing. However, as the greater part of the run had been made it was decided to continue the run with the same mixing valve adjustment.

The gas consumption was also higher than on the previous run.

No trouble was experienced in keeping the calorimeter temperatures at the desired points.

During this and the previous run light spring cards were taken, in order to obtain the back pressure caused by the cal-

orimeter, Several of these cards are shown on Page 45. The back pressure was about .8 of a pound at rated load.

The cards taken at full load, with a 240 pound spring, shown on Page 46, show clearly the irregularity of the action of the mixing valve. These cards were taken from cut-out to cut-out. The M.E.P. decreased with the increase in load.

The heat balance was plotted for both runs, in terms of the percent of total heat.

The exhaust gas loss was then calculated rationally , and also plotted.

The method of calculating the various losses is clearly shown on the preceding pages.

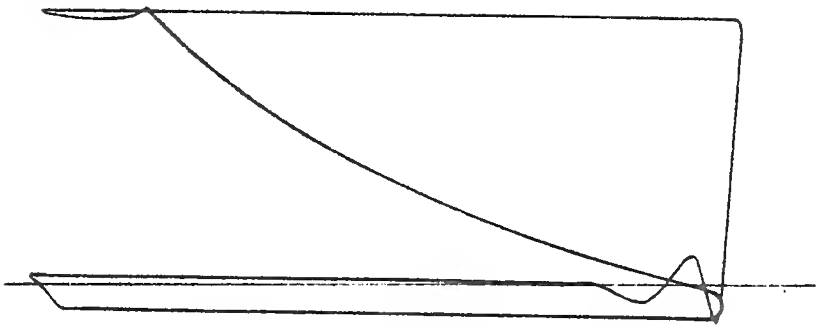


Fig. 10. Back Pressure Card
Run #1 Full Load.

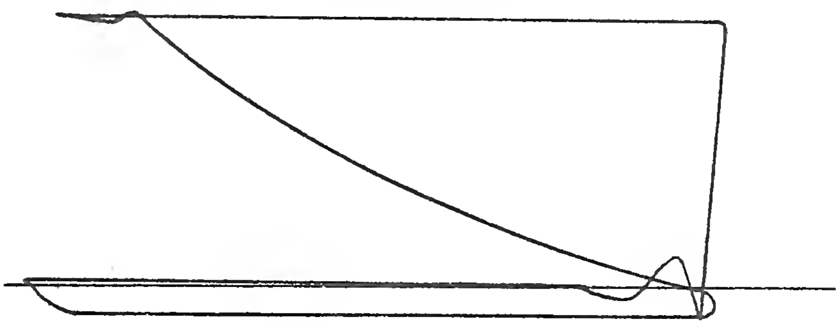


Fig. 11. Back Pressure Card
Run #2. Full Load.

In using the rational equations previously mentioned the voume of mixture was found by multiplying the piston displacement by the number of explosions and the temperature of the exhaust. The heat lost in the exhaust per hour is found by multiplying the weight of the exhaust gases per hour, by the specific heat, and by the temperature change. This can be expressed by the following formulae: $\text{B.T.U./ hr.} = \frac{WSQ(T-T')}{1 \text{ cu.ft.}}$

Where W = weight of mixture per hr.

Q = no. of cu. ft. of mix./hr.

S= Specific heat of mixture

T = temp. of Exhaust gases

T'= temp of room.

FIG. 12. INDICATOR CARDS FULL LOAD. RUN #1. M.E.P. 94.5 LBS.

FIG. 13.

RUN. #2. FULL LOAD CARDS.

M.E.P. 68.5 LBS.

CALCULATED HEAT IN EXHAUST GAS

Toatal displ = vol piston displ x EPMx 60

$$= 6.75 \times 6.75 \times \frac{3.14}{4} \times 11.94 \times 60 \times 35.5$$

= 1805 cu ft per hour.

Gas per hour = from log.

Air per hour = Total displ - gas per hour

= 1805 - 224.3 = 1580.7

$$\text{Air / hr. lbs} = \frac{\text{Air /hr cu ft}}{14.2}$$

$$= \frac{1580.7}{14.2} = 11.3 \text{ lbs /hr.}$$

Gas / hr.lbs = gas per hr. cu. ft x .084

= 224.3 x 0.084 = 18.8

Total lbs = 111.3 plus 18.8 = 130.1

BTU in EXH = lbs. exh gas x diff tempxSpec H.

= 130.1x(900-60) x 0.084

= 25,700

$$\text{\% lost in Exh} = \frac{25{,}700}{158000} = 16.3 \text{ \%}$$

SAMPLE CALCULATIONS

$$\text{CU.FT.GAS/HR.} = \frac{\text{GAS CON.} \times \text{ABS TEMP} \times \text{ST. PR.}}{\text{ST.ABS.TEMP} \times \text{PR. AT METER}}$$

$$\frac{18.7 \times 520 \times 30 \times 12}{522 \times 29.98} = 224.3 \text{ cu.ft/ hr.}$$

Cu ft / hr x heat value gas = BTU supplied/hr.

224.3 x 705 = 158,000. BTU supplied / hr.

I.H.P. x 2546 = heat equiv of IHP.

10.6 x 2546 = heat equiv of IHP.

$$\frac{\text{Heat equiv}}{\text{Heat supplied}} = \% \text{ heat in IHP.}$$

$$\frac{25{,}900}{158{,}000} = \% \text{ heat in IHP.}$$

Diff. in temp. x water / hr. = BTU in Exhaust

(82.5-53) x 99.5 x 12 = 35,160 BTU in Exhaust

$$\frac{35{,}160}{158{,}000} = 22.2 \% \text{ heat lost in Exhaust}$$

Diff in temp x Jacket water /hr. =BTU jacket

(102 -53) x 74.5 x 12 = 43,800 BTU in Jacket

$$\frac{43{,}800}{158000} = 27.7 \% \text{ heat lost in Jacket water}$$

PART FOUR

CONCLUSIONS

The heat of the exhaust gas as calculated rationally was about ten per-cent lower throughout both runs than that obtained by means of the calorimeter. This shows that either the mean specific heat or the temperature difference or both were assumed incorrectly.

Assuming that the exhaust temperature was 900 deg.F., the mean specific heat of the gas should have been assumed as 0.312, or if the mean specific heat was correct at 0.245, the temperature of the exhaust gas should have been assumed as 1250 deg.F.